METHOD AND APPARATUS FOR POLARIZATION MEASUREMENTS

CROSS REFERENCES TO RELATED APPLICATIONS

This application claims priority to U.S. provisional
5   application 60/228,265, entitled "Method and Apparatus for
Polarization Measurements," filed August 25, 2000, which
is incorporated herein by reference in its entirety.

This application is related to U.S. provisional
application 60/229,129, entitled "System Comprising In-
10 Line Wavelength Sensitive Polarimeter," filed August 30,
2000, which is incorporated herein by reference in its
entirety.

TECHNICAL FIELD
15   The invention relates to a method and apparatus for
polarization measurements and, more particularly, to a
method and apparatus for frequency-resolved polarization
measurements of an optical signal in wavelength division
multiplexed systems.
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BACKGROUND OF THE INVENTION
The demand for transmission capacity enhancement in
fiber networks and for low cost per bit for high bit-rate
systems requires continuous improvement in single channel
25 bit-rates. Electrical time division multiplexed (ETDM)
systems at bit-rates of 40 Gb/second per channel are
commercially available, and optical time division
multiplexed (OTDM) systems offering bit-rates of 160 Gb/s
per channel have been demonstrated.
30   Aside from other transmission impairments like
chromatic dispersion or non-linear pulse propagation,
polarization mode dispersion (PMD) remains an obstacle to
be overcome before these ultra high time division
multiplexed (TDM) systems can be implemented on a
35 significant number of installed fibers. Several different

PMD compensation and mitigation techniques have been proposed and partially demonstrated. They can be generally categorized according to concepts based on the electrical or optical domains of the system. Electrical

5   mitigation techniques possess advantages in terms of cost and size. However, the performance improvements from electrical techniques are generally not as great as those achievable with optical compensation techniques.

For example, optical techniques can be designed to be

10   bit-rate and format independent. The measurement of the polarized components of an optical signal may be used for implementing PMD compensation using optical techniques.

Aside from PMD compensation, simple polarization monitoring will also be an important feature in future

15   networks employing polarization multiplexing. Furthermore, polarization measurement is required as well for signal polarization adaptation to polarization sensitive receivers.

20   SUMMARY OF THE INVENTION

The invention relates generally to a method and apparatus for polarization measurements. A polarization state of an optical signal can be determined using a polarization analyzer comprising a polarization

25   controller, a polarizer, a wavelength dispersive element, and a photo-detector.

In one embodiment, the photo-detector is a photodiode array. To determine the polarization state of the optical signal, optical power measurements are performed as a

30   function of wavelengths within the optical signal for different settings of the polarization controller. The method can be applied to polarization and polarization mode dispersion determinations in wavelength division multiplexed (WDM) systems.

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BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings,

5 in which:

FIG. 1 is a schematic representation of a conventional polarization analyzer;

FIG. 2 is a schematic representation of a polarization analyzer according to one embodiment of the invention;

10 FIGS. 3a-c are schematic illustrations of multichannel detection of a dispersed optical signal;

FIG. 4 is a flow diagram of a method of polarization measurement according to one embodiment of the invention;

FIG. 5 is a schematic representation of a transmission

15 system incorporating one embodiment of the invention;

FIG. 6 is a schematic illustration of one example of a polarization analyzer of the invention; and

FIG. 7 is a schematic illustration of another example of a polarization analyzer of the invention.

20 To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

DETAILED DESCRIPTION OF THE INVENTION

25 The invention provides generally a method and an apparatus for measuring a polarization state of an optical signal. Polarization measurements can be performed using a polarization analyzer (or polarimeter) comprising a polarization controller, a polarizer, a wavelength

30 dispersive element, and a photo-detector. In one embodiment, the polarization state and the power of a broadband optical signal are obtained by measuring the Stokes vector components of the optical signal.

The method and apparatus can also be applied to

35 polarization mode dispersion (PMD) measurements. For

example, embodiments of the invention can be applied to
on-line measurements of polarization and PMD in a fiber
link of a wave division multiplexed (WDM) system without
data traffic interruption. By analyzing the frequency
5 dependence of the polarization of the optical signal at a
receiver input, the PMD characteristic of a WDM channel
for the corresponding frequency interval can be
determined. Results of the PMD measurements can be used
to derive PMD compensation parameters. Alternatively, PMD
10 compensation can also be implemented by measuring the
degree of polarization (DOP) of a WDM signal using the
polarization analyzer. Although the invention can be
practiced in conjunction with any type of PMD compensator,
it is particularly well-suited for use with optical
15 compensators.

    FIG. 1 is a schematic representation of a conventional
polarimeter 100, e.g., a model HP 8509A, available from
Hewlett-Packard, of Palo Alto, California. Details of
such a polarimeter 100 are disclosed in U.S. patent
20 5,227,623, entitled "Method and Apparatus for Measuring
Polarization Mode Dispersion in Optical Devices," which is
incorporated herein by reference in its entirety.

    An optical signal 150 having a polarization state to
be determined is coupled to the polarimeter 100 via an
25 optical connector 102. The optical signal 150 is directed
onto a spherical mirror 104 and split into four components
A, B, C and D by four adjustable quadrants of the
spherical mirror 104. As shown in FIG. 1, three of the
four components (A, B and C) are coupled into respective
30 polarizers P1, P2 and P3. Prior to entering the polarizer
P1, one of the optical signal components, e.g., A, is
passed through a waveplate 106. The waveplate 106 is used
to invert the polarization state of the signal component
A. Each polarizer P1, P2 and P3 is set to different
35 orientations, such that after passing through the

respective polarizers, the optical components, denoted by A', B' and C', are characterized by different polarization components.

The intensities or powers of the four optical signal
5 components A', B', C' and D are measured using photodiodes PD1, PD2, PD3 and PD4. The power of the fourth component, D, which is not filtered by any polarizer, is measured directly by the photodiode PD4. The photodiodes PD1, PD2, PD3 and PD4 provide four output photo-currents I1, I2, I3
10 and I4, which are proportional to the measured powers of the respective optical signal components A', B', C' and D. The Stokes parameters, which characterize the polarization state of the input optical signal 150, can be determined by analyzing the photo-currents I1, I2, I3 and I4, using
15 techniques that are known in the art.

FIG. 2 is a schematic representation of a polarization analyzer 200 according to one embodiment of the invention. The polarization analyzer 200 comprises a polarization controller 202, a polarizer 204, a wavelength dispersive
20 element 206, and a photo-detector 208.

The polarization controller 202 is used to perform defined polarization transformations of an incoming optical signal 250. Different types of polarization controllers 202 may be used to practice various
25 embodiments of the invention, including mechanical, electro-mechanical and electro-optical devices. In general, mechanical devices tend to be slow compared to electro-optical ones. Therefore, electro-optical polarization controllers, e.g., lithium niobate-based
30 devices, are preferable because they allow polarization state transformation to be performed at relatively high speeds, e.g., on the order of MHz.

In one embodiment, the polarizer 204 is a linear polarizer, and is selected to operate within a wavelength
35 region of the optical signal 250.

The wavelength dispersive element 206 is used to disperse, or separate, the optical signal 250 into its spectral components within a wavelength range from λ_{min} to λ_{max}, where λ_{min} and λ_{max} denote the lower and upper

5 wavelength limits for the spectral range of the optical signal 250. Depending on their wavelengths, different spectral components are dispersed into different angles. It should be noted that the wavelengths λ_i and λ_j are used to denote spectral components characterized by central

10 wavelengths λ_i and λ_j, though each spectral component may further be characterized by a spectral range around the central wavelengths.

The polarization analyzer 200 is generally applicable to polarization measurements of input optical signals

15 having either monochromatic or broadband spectra. For WDM applications, the optical signal 250 typically has a spectrum residing in telecommunication windows around 1.3μm, 1.5μm and 800nm regions. In principle, the polarization analyzer 200 can be adapted to these signal

20 wavelength regions.

The wavelength dispersive element 206 should have a bandwidth that is sufficiently large to encompass the bandwidth of the optical signal 250. In one embodiment, the wavelength dispersive element 206 is a grating, e.g.,

25 a diffraction grating, with a bandwidth of about 32 nm and a spectral resolution of about 0.1 nm. Other types of wavelength dispersive element 206 may also be used, e.g., a fiber grating, a prism or scanning etalon. In general, it is preferable that the wavelength dispersive element

30 206 does not involve mechanical scanning, in order to have improved reliability and increased speed for polarization measurement of a broadband signal.

Referring to FIG. 2, the dispersed spectral components (λ_i, λ_j, ...) of the optical signal 250, which are

35 separated spatially as a function of wavelength, are

detected by a photo-detector 208. In one embodiment, the photo-detector 208 is a photodiode array, which comprises a series of pixels for detecting the dispersed spectral components (λ_i, λ_j, ...) of the optical signal 250. One

5 example of the photodiode array 208 is an optical channel monitor, which can be used for wavelength, power and optical signal to noise ratio (OSNR) measurements. Details of an optical channel monitor have been disclosed in U.S. Patent 6,078,709, entitled "Method and Apparatus

10 for Monitoring Multi-Wavelength Optical Systems," issued on June 20, 2000, and in U.S. Patent 6,002,822, entitled "Article Comprising An Optional Waveguide Tap," issued on December 14, 1999, both of which are incorporated herein by reference. It is understood that other photodiode

15 arrays or optical channel monitors may also be suitable for practicing embodiments of the invention. If the polarization analyzer 200 is used to measure polarization of a monochromatic optical signal, then a single photo-detector or photodiode may also suffice.

20   For WDM applications, spectral resolution of the polarization analyzer 200 is an important design parameter. The spectral resolution of the polarization analyzer 200 is determined by the combined resolution of the wavelength dispersive element 206 and that of the

25 photodiode array 208. In order to perform frequency-sensitive (or wavelength-dependent) polarization measurements corresponding to different spectral components, the resolution of the polarization analyzer 200 should be sufficiently high to ensure that the

30 resolved frequency interval is small enough such that the Stokes vector remains substantially constant within the resolution interval. In general, the appropriate resolution depends on the degree of accuracy that is desired for the polarization measurements, and may vary

35 according to the specific needs or applications. It is

understood that one skilled in the art would select a
resolution to provide measurements within acceptable
limits for specific applications.

 5   FIG. 3a illustrates schematically the detection of the
dispersed spectral components (e.g., λ_i, λ_j, λ_k, ...) by
different pixels or channels (PX_i, PX_j, PX_k, ...) of the
photodiode array 208. With sufficiently high resolution,
each pixel of the detector array 208 detects a portion of
the spectrum of the optical signal 250, corresponding to a
10 spectral component that is sufficiently narrow such that
there is no significant change in the Stokes vector, or
polarization. As illustrated in FIG. 3a, spectral
components λ_i, λ_j, λ_k (each with its associated spectral
range $\Delta\lambda_i$, $\Delta\lambda_j$, $\Delta\lambda_k$), are detected respectively by adjacent
15 pixels PX_i, PX_j, and PX_k. If the Stokes vectors for the
spectral components λ_i, λ_j, λ_k remain substantially constant
within their respective spectral ranges, the optical
powers detected by pixels PX_i, PX_j, and PX_k will correlate
with the polarization parameters for the respective
20 spectral components.

   In contrast, FIG. 3b illustrates schematically the
detection of dispersed spectral components with
insufficient resolution of the polarization analyzer 200.
As shown in FIG. 3b, one pixel 301 of the photodiode array
25 208 simultaneously detects several spectral components λ_i,
λ_j, λ_k, each with slightly different polarization vectors
S_i, S_j, S_k. The intensity (or contribution) of each
spectral component, as detected by the pixel 301, is
determined by the filter function of the wavelength
30 dispersive element 206. Thus, instead of detecting signal
contribution from one polarization state corresponding to
a specific spectral component, the pixel 301 measures an
average polarization state with a degree of polarization
(DOP) smaller than one. The DOP describes how
35 polarization vectors of different spectral components are

aligned with respect to each other within the wavelength resolution of one pixel. If the polarization vectors are completely aligned, then DOP is at a maximum value of one. However, if the polarization vectors are not completely

5 aligned, then DOP is less than one.

FIG. 3c illustrates yet another scenario in which each of the spectral components λ_i, λ_j is detected by several detector pixels of the photodiode array 208. In this example, the spectral component λ_i is detected by three

10 pixels 303, 305 and 307; while the spectral component λ_j is detected by three pixels 307, 309 and 311. Since pixels 303, 305, 309 and 311 contain signal contribution from only one spectral component λ_i or λ_j, the photo-currents from these pixels (e.g., sum of 303 and 305 and sum of 309

15 and 311) are proportional to the signal intensity for the individual spectral components λ_i and λ_j. Although the photo-current from pixel 307 contains contributions from both spectral components λ_i and λ_j, it may still be possible to extract, using appropriate signal processing

20 techniques, individual signal contributions for the determination of the polarization states for the spectral components λ_i and λ_j.

In general, for WDM applications, the polarization analyzer 200 should have sufficient resolution to avoid

25 polarization averaging over a wavelength interval in which the polarization or optical power can significantly vary. For example, it is preferable to avoid polarization averaging within one pixel, such as that illustrated in FIG. 3b, or at least within the signal bandwidths of

30 adjacent WDM channels.

Method of Polarization Measurement

The polarization state of an optical signal can be determined using the polarization analyzer 200 of FIG. 2

35 by measuring the powers of the optical signal

corresponding to several different polarization transformations of the polarization controller 202.

FIG. 4 is a flow diagram of a method of polarization measurement according to one embodiment. In this
5 embodiment, the Stokes vectors for the spectral components of the optical signal are measured and the polarization state and optical power of an optical signal can both be determined from the Stokes components.

The method can generally be applied to a variety of
10 optical signals with different spectral ranges. For example, the optical signal may have a wavelength range in the 1.55 μm region, such as one that is used in WDM systems. Alternatively, the optical signal may have a broadband spectrum in other wavelength regions.
15 Furthermore, the method may also be applied to a monochromatic optical signal.

At step 401, an input optical signal, characterized by an arbitrary polarization state to be determined, is launched into the polarization analyzer 200. At step 403,
20 the polarization controller 202 is set to a first position, and the optical signal is converted from its arbitrary polarization state to a transformed polarization state PC1.

At step 405, the optical signal is directed to the
25 linear polarizer 204, which is set at a fixed orientation to define a polarization axis for the exiting optical signal.

At step 407, the optical signal exiting the polarizer 204 is directed onto a wavelength dispersive element 206,
30 which disperses the spectrum of the optical signal 250 as a function of wavelength. In general, the dispersed spectrum of the optical signal 250 may correspond to a continuum of wavelengths, or to a spectrum consisting of wavelengths corresponding to separate communication
35 channels. In either case, the dispersed spectrum can be

considered as being made up of different spectral
components, with each spectral component characterized by
a central wavelength and an associated spectral range (or
spectral width). In the case of a WDM optical signal, one
5 or more of the spectral components may correspond to
individual optical channels of the WDM system.

    At step 409, the optical powers of the spectral
components are measured by a photo-detector 208 such as a
photodiode array. Each of the spatially separated
10 spectral components may be directed to one or more pixels
of the photodiode array 208. A photo-current, which is
proportional to the optical power of the detected spectral
component, is generated in the photodiode array 208. The
magnitudes of the measured photo-currents for the
15 respective spectral components of the optical signal may
be stored in a memory or processor for calculation of the
Stokes components of the optical signal.

    There are two aspects in practicing the invention for
WDM applications. One aspect involves measurements of
20 wavelength-dependent polarization (e.g., for a signal with
a non-zero PMD), in which case, each signal corresponding
to a WDM channel, which may comprise several spectral
components, illuminates (i.e., be detected by) several
pixels. However, at least some pixels of the photodiode
25 array should each detect primarily a frequency or
wavelength range within which the Stokes vector remains
substantially constant, in order to avoid polarization
averaging.

    The other aspect involves measuring the degree of
30 polarization (DOP) of the optical signal. In this case,
it is sufficient that each signal corresponding to a WDM
channel illuminates only one pixel in the photodiode array
(even if the polarization state changes within the
bandwidth of one WDM channel), as long as no two signals
35 corresponding to two WDM channels illuminate the same

pixel. However, the resolution of the polarization
analyzer, which can be limited by the wavelength
dispersive element, should at least be sufficiently high
to avoid polarization averaging between different WDM
5 channels. In either aspect of practicing the invention,
the resolution is selected to provide measurements within
acceptable tolerance for the specific applications.

Similar optical power measurements are subsequently
performed, as shown in step 411, with the polarization
10 controller 202 set to at least three other positions, each
of which is different from the first position and from
each other. In general, many different combinations of
four positions may be used for the polarization controller
202 in performing the polarization measurement according
15 to the method of the invention. For example, one possible
combination of four settings of the polarization
controller 202 may consist of launching a signal with
transverse electric (TE) mode into the polarization
controller 202. The polarization controller 202 may be
20 set sequentially to produce four output or transformed
polarization states. If one uses a Poincare sphere
representation of Stokes vectors for describing the
polarization states of the signal, then these four
transformed polarization states should preferably have
25 maximum spacings from each other on the Poincare sphere --
e.g., forming a tetrahedron.

For each of the spectral components, the measured
optical powers corresponding to the four positions of the
polarization controller 202 may be analyzed, using
30 relationships that are known in the art, to generate or
calculate the Stokes vector components, or Stokes
parameters, which describe polarization and optical power
of the optical signal.

In general, the four power measurements are related to
35 the four Stokes parameters by a 4x4 matrix, known as a

calibration or instrument matrix, which may be determined
by a calibration procedure known in the art. Details of a
suitable calibration procedure has been described by
R.M.A. Azzam, in "In-line, Light-Saving Photopolarimeter
5 and its Fiber-Optic Analog", Optics Letters, Vol. 12, No.
8, pp.558-560, 1987, which is incorporated herein by
reference in its entirety. Depending on the wavelength
dispersive element, or optical couplings between the
polarization controller, the polarizer and the wavelength
10 dispersive element, the calibration matrix may potentially
be different for every detector pixel. Once the
calibration matrix has been determined, the four Stokes
parameters can be obtained by multiplying the four power
measurements generated by each detector pixel with the
15 corresponding calibration matrix for the detector pixel.

The polarization state corresponding to the spectral
components may then be determined from the Stokes
parameters. It is noted that power measurements
corresponding to at least four transformed polarization
20 states PC1, PC2, PC3 and PC4 (corresponding to four
positions of the polarization controller 202) are
necessary to provide sufficient data to determine the
original polarization state described by the Stokes vector
and the power of the input optical signal. Additional
25 measurements, i.e., corresponding to more than four
transformed polarization states, are not precluded,
although they are not necessary.

It is understood that the method of FIG. 4 illustrates
only one application of the polarization analyzer 200.
30 Thus, the polarization analyzer 200 may also be used in
other applications which do not require measurements
corresponding to four different settings of the
polarization controller 202. For example, if the power of
the input optical signal is not required, then less than
35 four measurements may suffice to provide polarization or

other desired information for the optical signal. Thus, depending on the specific information desired, the polarization analyzer 200 can generally be used for various optical measurements by generating different
5 numbers of transformations corresponding to different positions (may be more than or less than four) of the polarization controller 202.

Several examples are provided below to further illustrate different polarization transformations that can
10 be used for practicing the invention.

Example 1

FIG. 6 is a schematic illustration of a polarization analyzer 600, comprising a polarization controller 602, a
15 polarizer 608, a wavelength dispersive device 610, and a photodetector array 612. In this example, the polarization controller 602 consists of a half-wave plate 604 and a quarter-wave plate 606. An optical signal 650 having a certain polarization state passes through the
20 half-wave plate 604, the quarter-wave plate 606 and the polarizer 608. After exiting the polarizer 608, the optical signal 650 is dispersed by the wavelength dispersive device 610, and the dispersed signal is subsequently detected by the photodetector array 612.
25 The orientations of the half-wave plate 604, the quarter-wave plate 606 and the polarizer 608 are represented respectively by $\theta_{1/2}$, $\theta_{1/4}$ and θ_a. Table 1 provides one example of the four positions or transformations of the polarization controller 602 (each
30 position being defined by $\theta_{1/2}$, $\theta_{1/4}$ and θ_a) that can be used for practicing the invention. The orientations of the half-wave plate 604 and the quarter-wave plate 606 are given as angular rotation (in degrees) relative to the orientation of the polarizer 608. By performing power
35 measurements for the dispersed signal at each of the four

positions of the polarization controller 602, Stokes parameters for the optical signal 650 can be obtained and used for the determination of the polarization state of the optical signal.

5

Table 1

	$\theta_{1/2}$	$\theta_{1/4}$	θ_a
1	0	0	0
2	22.5°	0	0
3	45°	0	0
4	22.5°	45°	0

15 In another embodiment, the order of the half-wave plate 604 and the quarter-wave plate 606 may be interchanged such that the optical signal 650 passes through the quarter-wave plate 606 before the half-wave plate 604. In that case, the orientations of the half-wave plate 604 and the quarter-wave plate 606 20 corresponding to the four transformations of the polarization controller 602 will be different from those shown in Table 1. One skilled in the art will be able to devise suitable orientations for practicing alternative embodiments of the invention.

25

Example 2

FIG. 7 is a schematic illustration of a polarization analyzer 700, comprising a polarization controller 702, a polarizer 704, a wavelength dispersive device 706, and a 30 photodetector array 708. In this example, the polarization controller 702 is a quarter-wave plate with an orientation denoted by $\theta_{1/4}$. To practice the invention, an optical signal 750 having a certain polarization state passes through the polarization controller 702 and the 35 polarizer 704. The signal 750 exiting the polarizer 704

is dispersed using the wavelength dispersive device 706, and the dispersed signal is detected by the photodetector array 708.

5   With the polarizer 704 maintained at a fixed orientation θ_a, the orientation $\theta_{1/4}$ of the polarization controller 702 is varied continuously as a function of time - e.g., by rotating the quarter-wave plate through different positions at a given rate. The dispersed signal intensity (I) detected by the photodetector array 708 can
10   be represented by the following equation:

$$I = 0.5 \; [(S_o + S_1/2) + (S_1/2)\cos(4\theta_{1/4})$$
$$+ (S_2/2)\sin(4\theta_{1/4}) - S_3\sin(2\theta_{1/4}) \qquad \text{Eq. (1)}$$

15   where S_o, S_1, S_2, and S_3 are the respective Stokes parameters of the optical signal 750.

    The Stokes parameters S_o, S_1, S_2, and S_3 may be obtained by performing a Fourier analysis of the detected signal spectrum. By performing Fourier analysis for all
20   spectral components, a wavelength dependent polarization of the optical signal 750 can be determined. Techniques of performing Fourier analysis for single wavelength applications have been disclosed in "Survey of Methods for the Complete Determination of a State of Polarization", by
25   P.S. Hauge, in SPIE vol. 88, Polarized Light, pp.3-10, 1976, which is incorporated herein by reference in its entirety.

Example 3
30   In another embodiment, the polarization analyzer may be used to measure spectral power density of an optical signal having a certain polarization state. In this case, it is only necessary that the polarization controller be set at two different positions to provide the
35   transformations necessary for power density measurements.

In one example, the two positions of the polarization
controller may differ from each other by 90°, producing
transformations corresponding to the TE and TM modes
respectively. Depending on the specific applications,
5   different numbers of orientations of the polarization
controller may also be used to generate other optical
measurements, as appropriate.

On-line PMD Measurement in a Transmission System
10   According to another aspect of the invention, the
polarization analyzer 200 can be used for measurement of
polarization mode dispersion (PMD) in a transmission
system. In particular, it can be used as part of a PMD
monitoring unit for on-line PMD measurement, concurrent
15 with data transmission (i.e., without interrupting data
transmission) in a WDM system. On-line PMD measurements
using a conventional polarization analyzer has previously
been disclosed in a commonly-assigned U.S. patent
application, Serial No. 09/518,296, entitled "Method and
20 Apparatus for On-Line Monitoring of Polarization Mode
Dispersion in a Transmission System," filed on March 3,
2000, which is herein incorporated by reference in its
entirety.
        FIG. 5 shows a schematic diagram of a WDM transmission
25 system 500 containing a PMD monitor 550 for on-line PMD
measurement. The PMD monitor 550 comprises a polarization
switch 502 and the polarization analyzer 200.
        In the WDM transmission system 500, different
transmitters (TX1, TX2, ..., TXN) are used to generate
30 light (or optical carrier) at different wavelengths for
data transmission. The carrier signals are modulated by
respective data bit streams to form data signals DS1, DS2,
..., DXN. These data signals DS1, DS2, ..., DXN, having
different carrier wavelengths are combined in a multiplexer
35 510 to form a single optical signal 580.

The optical signal 580, which is illustratively, linearly polarized, is coupled into a polarization switch 502 before entering the transmission line 512. The polarization switch 502 allows the output polarization of

5 the optical signal 580 to be varied. For example, the optical signal 580 may be switched between two non-orthogonal linear polarization states, which have a relative angle of 45° (in Jones space) with respect to each other. Many devices may be used as the polarization switch

10 502 for rotating the polarization of the optical signal 580, with one example being a Pockels cell.

In the schematic representation of FIG. 5, it is assumed that the transmission fiber 512 represents the entire transmission line characterized by a polarization

15 mode dispersion (PMD) to be monitored using embodiments of the invention. At its output end 514, the transmission fiber 512 is connected respectively to the polarization analyzer 200 and a PMD compensator 516. As such, the transmission signal 580 is split into two portions -- one

20 portion 580a being coupled into the polarization analyzer 200, and another portion 580b being coupled to the PMD compensator 516.

The polarization analyzer 200 is also connected to a computer or a microprocessor 518 that communicates with the

25 polarization analyzer 200 and a controller 520 for controlling the PMD compensator 516. Alternatively, the controller 520 may be incorporated as part of the computer 518.

The PMD compensator 516 is connected at its output 522

30 to a demultiplexer 524 for separating the transmitted signal 580b into its respective channel components DS1, DS2, ..., and DSN. The optical signals of the respective channels are detected by a number of receivers RX1, RX2, ..., RXN. Typically, the polarization analyzer 200 and the

35 PMD compensator 516 are located in close proximity to the

receivers RX1, RX2, ..., RXN, to allow accurate PMD compensation for the data signal 580b arriving at the receivers RX1, RX2, ..., RXN.

5   In an alternative embodiment, the polarization analyzer 200 may be connected to the output 522 of the PMD compensator 516 such that the transmitted signal 580 exiting the PMD compensator 516 may be split into two portions, with one portion directed to the polarization analyzer 200, and another portion to the demultiplexer 524.

10   This arrangement is illustrated in phantom in FIG. 5.   In general, the polarization analyzer 200 of the invention can be used in conjunction with any PMD compensator 516, including electrically-based and optically-based compensators.

15   The polarization switch 502 and the polarization analyzer 200, which collectively form the PMD monitor 550, can be used to provide real-time, on-line PMD measurements for the transmission fiber 512. Since the signal source used for PMD measurement is provided by the transmission

20   or data signal 580 (as opposed to an external signal source), embodiments of the invention allow PMD measurements to be performed concurrent with data transmission in the transmission system 500, without interrupting data transmission.

25   To determine the PMD of the transmission fiber 512, it is necessary to perform polarization measurements for at least two different and non-orthogonal polarization states of the optical signal 580 launched into the transmission fiber 512. For example, with the polarization switch 502

30   set at a first orientation, a first set of polarization measurements may be performed according to steps such as those outlined in FIG. 4. Subsequently, a second set of polarization measurements is performed with the polarization switch 502 set at a second orientation, e.g.,

35   about 45° with respect to the first position. It is noted

that polarization switching should not affect the signal propagation in an intensity modulated direct detection (IMDD) system, at least in the absence of fiber nonlinearities, as long as polarization dependent losses

5   can be neglected, and PMD has been compensated for. The measured wavelength dependency of the Stokes vectors (i.e., polarization measurement as a function of wavelength) allows determination of PMD in the transmission fiber 512.

10   Results of these measurements are provided as input data to the computer or microprocessor 518, which then computes relevant parameters for the adjustment of the PMD compensator 516. Alternatively, based on results of the PMD measurements, PMD compensation parameters may also be

15 retrieved from a look-up table that may be stored in the computer 518. These parameters are communicated to the controller 520 which then adjusts the PMD compensator 516, such that the optical signal 580b arriving at the demultiplexer 524 is compensated for any pulse distortion

20 due to PMD in the transmission system 500.

        According to another aspect of the invention, the polarization analyzer 200 may also be used to measure the degree of polarization (DOP) for PMD monitoring purpose – through measurement of the Stokes vectors of the

25 transmitted signal 580. For example, the DOP may be used as an indicator of the presence of PMD in the transmitted signal 580, and such information may be used by the processor 518 to generate a control signal for controlling the PMD compensator 516.

30   In one embodiment, the polarization analyzer 200 is connected to the output of the PMD compensator 516, such that one portion of the transmitted signal 580 enters the polarization analyzer 200 and the other portion enters the demultiplexer 524. The DOP may be measured using the

35 polarization analyzer 200 by performing optical power

measurements for individual WDM channels, which are resolved by passing the transmitted signal 580 (after propagating through the polarization controller and the polarizer 202 and the polarizer 204) through the

5 wavelength dispersive element. The optical powers measured by the detector array 208 corresponding to each of the individual WDM channels are then used to calculate Stokes components for the WDM channels, which in turn allows a determination of the DOP. The DOP data can be

10 analyzed to derive information about PMD, which can then be used for controlling the PMD compensator 516.

Although several preferred embodiments which incorporate the teachings of the present invention have been shown and described in detail, those skilled in the

15 art can readily devise many other varied embodiments that still incorporate these teachings.